17th European Photovoltaic Solar Energy Conference, Munich, Germany, 22-26 October 2001

PV SOLAR ELECTRICITY: ONE AMONG THE NEW MILLENNIUM INDUSTRIES

Winfried Hoffmann
RWE Solar GmbH
Industriestrasse 13, 63755 Alzenau, Germany
Phone: +49-(0)6023 91-1710, Fax: +49-(0)6023 91-1729
email: winfried.hoffmann@solar.rwesolutions.com

ABSTRACT: During recent years, solar electricity generation based on photovoltaics has developed into an industry at annual growth rates above 20%. Major market segments served by this industry comprise consumer applications, remote industrial systems, developing countries, and grid-connected systems. The potential in these markets supports sustained future growth, particularly for applications in developing countries and grid-connected systems in the industrial countries, where PV-generated electricity eventually will start to compete with peak grid power. Backed by price experience curves and a laboratory proven technology road map, a module turnover representing 100 billion € in 2030 and providing employment for several million people worlwide can be extrapolated. A sustainable energy contribution to the worldwide energy mix in subsequent decades is foreseen as a result of competitive PV solar electricity applications.
Keywords: PV Market Growth – 1: Strategy – 2: Cost Reduction – 3

1. THE PV SOLAR ELECTRICITY JIGSAW PUZZLE

Photovoltaics (PV) – the direct conversion of sunlight into electricity – has by now reached a high degree of maturity and accounts already for over 1 GWp of accumulated power sold so far. Present applications range from a wide variety of terrestrial applications to powering the ever-increasing number of satellites.

With the onset of the new millennium, the more scientifically oriented term photovoltaics must now stand for the ultimate goal of its use, i.e. for solar electricity. For PV solar electricity to become a distinct contribution to the world’s energy needs, substantial growth rates must further build on new multi-megawatt production facilities. The prime responsibility for these rests with the big industrialized nations – USA, Japan, countries in Europe and in Asia – and here, in turn, both on bold initiatives by their industries, as well as on the rising public and political awareness for the need of necessary energy and industry policies. The increasing momentum and volume thus being provided will eventually suffice to put the photovoltaic industry on a viable foundation, and ultimately to generate significant contributions and reap the benefits of clean renewable energy.

PV solar electricity comprises various interacting aspects that must fit together to form a consistent “picture” of solar electricity. This is visualized by various building blocks in the form of jigsaw puzzle elements (see Fig. 1).

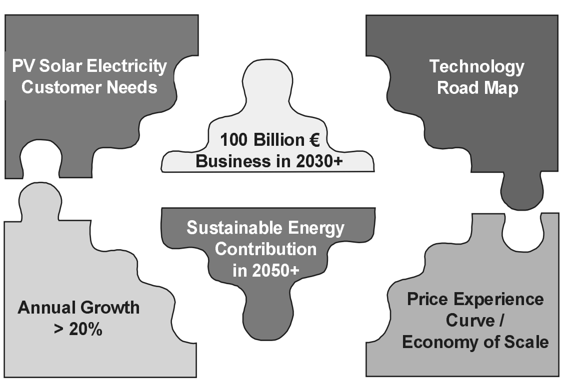


Fig. 1: PV Solar Electricity Puzzle

The main building blocks are representative of

- customer needs today and tomorrow;
- growth projections of over 20% annually, anticipated from the growth of the various market segments;
- an ongoing experience to support price experience curves;
- a technological “road map”, being prepared by today’s active and multi-facetted research and development;
- an industry of about 100 billion € anticipated to be reached around 2030;
- finally, based upon the fitting of these building blocks the ultimate development of a growing sustainable energy contribution by around 2050, when PV will be able to significantly impact global electricity generation.

These building blocks forming the picture of solar electricity must fit into the larger picture of all aspects and forms of electricity generation at large. At the end of this paper when the puzzle elements fit together, it will be readily seen why PV solar electricity has all the ingredients to become one among the new millennium industries.

2. THE GLOBAL PV SOLAR ELECTRICITY MARKET

2.1 Historic Growth

The growth of the global PV market over the last 20 years is shown in Fig. 2. [1, 2] The first lesson learned is seen when a forecast in the early 80s is compared with the real growth that actually occurred thereafter.

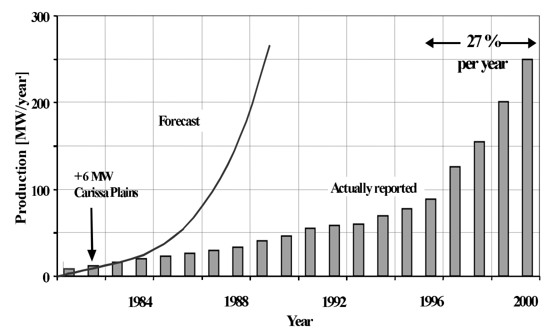


Fig. 2: Historic PV Solar Electricity Market Growth

Big changes within a short period of time should be analyzed carefully. If those changes can be attributed only to one or few projects rather than to market development, the respective yearly growth should never be used as an extrapolating tool. This is readily seen in the already mentioned early market projection, when in 1983 one particular 6 MW US project (Carissa Plains) induced a big growth, which declined upon finishing to the small growth number as before. This problem is most pronounced if the size of the single project is similar to the size as of the rest of the market.

The last 5 years demonstrated high growth rates averaging to as high as 27% per year and reaching 250 MW in the year 2000. The PV market for terrestrial applications may be divided into 4 major segments, identified by the terms

- consumer,
- remote industrial,
- developing countries,
- grid-connected.

Whereas the market in the past basically developed from consumer products and remote industrial applications, the contributions of the market segments have shifted towards grid-connected systems, followed by installations in developing countries. (Fig. 3).

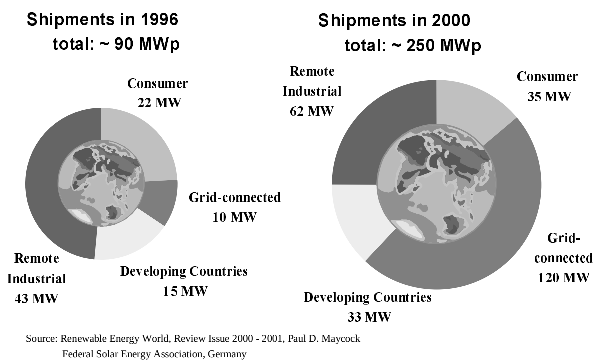


Fig. 3: Recent Growth for the Main Market Segments

2.2 Future Growth, Customer Use and Competitiveness

The future market growth in the coming three decades until 2030 is shown in Fig. 4. This semi-log plot shows annual growth rates in the range of 20 up to 25% per year.

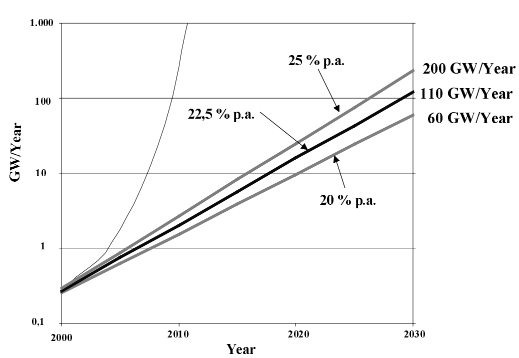


Fig. 4: Future PV Solar Electricity Growth

Throughout the paper reference is made to an intermediate growth of 22.5% per year. In order to get a feeling for these anticipated high annual outputs in future years, we take a look at some specific examples for each of the main market segments.

Market performance is governed by profitability that in turn may be determined by available alternatives for the same application. The relationship between power sold, and corresponding revenues is quite dependent on the market segment, or even on the actual product. One may define a corresponding "figure-of-merit" for the different applications that establishes a price relationship.

2.2.1 Consumer applications

Solar calculators were among the first applications of this category. Today solar watches, battery chargers, and various products of the leisure industry are equipped with small integrated PV modules. The overriding reason for choosing PV supplies is less cost by powering with PV compared to battery supplies, and thus more comfort without necessary replacement and proper disposal of used batteries. In the consumer market the module price is governed by the total price of the particular item, i.e. by price/piece. For all other PV market segments, comfort and also prestige may play a role, but mainly quantitative cost comparisons hold. In recent years solar modules are more and more used to power the electricity needs in smaller boats and yachts. Since about 5 years solar sun roofs could be ordered as an option from the German car manufacturer Audi. This integration of solar cells in the car body should serve as one example how just one product can contribute quite significantly to the overall market.

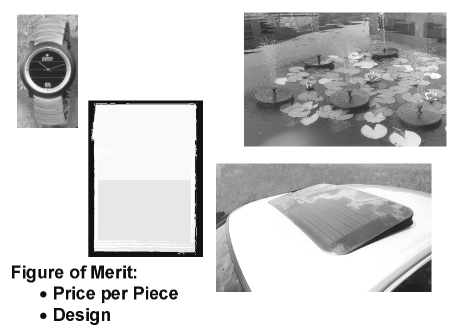


Fig. 5: Consumer Applications

In the future, more and more automobiles may be equipped with PV solar roofs to power car ventilation of parked cars for cooling, and to decrease fuel consumption by supplying the increasing power demand for car electronics. Once the car manufacturers realize that by including a solar panel their total production cost is reduced by serving a customer need even better, more and more car manufacturers will take advantage of this new technology (e.g. by decreasing the peak power of the air conditioning system and thus saving cost, while offering a much more comfortable – because cooler – environment to the driver, when he enters the car after parking in the sun). It seems reasonable that like every car today has a battery, each car in 20-30 years might have solar cells incorporated into the car body. Assuming 60 to 80 million cars per year (from today's 60 million sold per year) each to be equipped with solar cells of about 50W, this consumer application alone will require around 3-4 GW/year.

2.2.2 Remote industrial

For remote industrial applications hybrid systems are customary, where a PV generator is backed by batteries, and possibly by an additional diesel generator. The conventional alternative is a diesel generator alone, backed by batteries. The systems include mainly power supplies too far to be connected to the power grid, telecommunication, traffic signals, and geographical position systems.

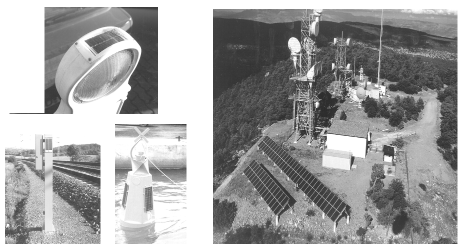


Fig. 6: Remote Industrial Applications

As a specific example, the cost of electricity generation is compared between a 5 kW diesel/battery system and a 1.8 kW PV/ 5 kW diesel/battery system. The result [3] shown in Table 1 demonstrates the clear cost advantage of the PV-equipped system, which is particularly pronounced in case of a relatively short life time of batteries.

Table 1: Profitability Increase by Adding PV to a Diesel-Battery System (from Universität Gesamthochschule Kassel [3])

Electricity generating cost [€ / kWh]	Standard lifetime of Diesel and battery	Reduced lifetime of battery to 1 year
Diesel (5 kVA) @ 100% Battery	3,0 € / kWh	5,3 € / kWh
Diesel (5 kVA) @ 25% Battery PV (1,8 kWp) (@ 5 kWh / m^2 x d)	2,2 € / kWh	3,1 € / kWh

Generally in this market segment, where highly reliable power sources are needed, long lifetime and high efficiency are the criteria that are valued in terms of price/W.

Another example may serve to gauge the size of the future market: The worldwide spread of mobile telephones is well known. In order to cover not only the more densely populated areas, but as well the urban less densely populated areas – even in industrialized countries - a global demand of up to a million transmitter stations annually, each with a 0.5 to 1kW solar generator, seems realistic, resulting in 0.5 to 1 GW for only this one application. As a reference: in Germany there are about 300,000 base and repeater stations (GPS) installed. For UMTS about 3 times as many will be needed in the future, and a better coverage of less populated areas will increase this number as well.

2.2.3 Developing countries

In 2030 there are most probably about 2 to 3 billion people still without electric light and other amenities of the industrialized world. Solar home systems, small village grids, and also water pumping may greatly alleviat

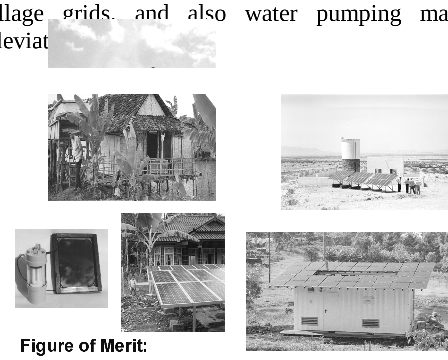


Fig. 7: Solar Electricity in Developing Countries

For solar home systems in developing countries both cost and service are important. The average monthly cost has been estimated [4]: For non-PV-equipped homes, batteries, candles, and kerosene amount to 6 to 8 US$/month. A 50W PV system with battery and charge controller represents an investment of about 500 US$, that together with batteries results in about 7 US$/month over a time period of about 6 to 10 years, under the assumption of a low interest loan (e.g. World Bank, national institutions that support developing countries like KfW and others). However, here the intangible aspect of comfort is quite obvious. In terms of the equipment performance, the operational life, rather than the efficiency, is important, and hence it is the price/service that counts.

Assuming annual installations of 20 to 40 million solar home systems at 50 W each, 2 to 5 million water pumping at 1 kW each, 0.2 to 0.5 million village grids at 50 kW each, and 0.5 to 1 million hybrid systems at 10 kW each, add up to 30 GW/year in 2030. Integrated within the hybrid systems is a very important application, a PV-backed Suntainer® equipped with a parabolic antenna and a computer getting access to the worldwide web at any point on the globe. Thereby an agricultural cooperative can offer its products in time, when they are ready for sale. This could solve the main hurdle for financing solar electricity products in developing countries by creating enough return in a much shorter time period compared to Solar Home Systems when selling the agricultural products to the customer.

2.2.4 Grid-connected systems

Today, typically building integrated roof or façade PV systems are embedded in industry – political programs like the 100,000-roof program of Germany, the 70,000-roof program of Japan, and the Million Solar Roofs

Initiative of the United States. Combined this will represent 3.5 GW installed (assuming 3 kW per installation), which amounts to about one third of the cumulated power installed by 2010. The potential for more roofs, by orders of magnitude, available for peak grid support will be demonstrated later. Other examples of this market segment are sound-barrier walls along highways, shading of parking lots, and many more.

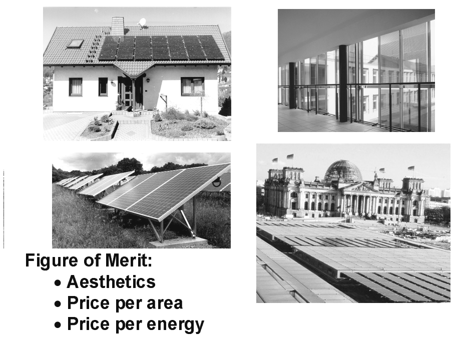


Fig. 8: Grid-connected PV Systems

Grid-connected systems are valued according to two different figures-of-merit, depending on the type of application. For stand-alone or most roof systems it seems appropriate to go by price per energy generated, i.e. price/kWh. This is understandable particularly in view of certain subsidy, reimbursement or feed-in programs (like the German 99 Pfennig/kWh EEG programs and Green Pricing models), that all depend on the total energy fed into the grid. Thus these grid-connected systems are selected according to the best price/kWh.

For a number of building integrated applications, like facades, and semitransparent PV windows, aesthetics are equally important as electrical properties. Furthermore in this case the PV module area competes with other building materials. Thus the price per module area counts, i.e.price/m².

Except for certain building integrated applications, the electricity-generating costs directly compete with those charged by the power utilities. The latter distinguish between bulk power and peak power. For solar electricity the geographical location of the PV installation directly affects the generating costs, depending on the corresponding insolation. In Germany, e.g., 1-sun insolation amounts to 900 h/year, while in Southern Europe it is 1800 h/year. In Fig 9, reference is made to turnkey prices for PV solar electricity system during the past 10 years in Germany. Starting from the early 1000-roof program in Germany in 1990 customers had to pay about 13 €/W_p installed system which in 2000 has decreased to 8 €/W_p. This corresponds to an annual price decrease of about 5%. Taking the latter price and using a formula to calculate the PV solar electricity generating cost [5] for a kWh the result is 0.60 €/kWh and 0.30 €/kWh in northern and southern locations, respectively, without any subsidy taken into account. With the assumed growth, it can be assumed that a similar cost reduction of 5%/year will occur in the future as will be shown later by a price experience curve for the most cost-contributing item, the solar module.

For the power utilities worldwide a mixture of base-, "medium"- and peak power electricity has to be provided to serve the varying load requirements from the customers. In the past when a regulated market existed worldwide, it was common practice to allow for a certain over-capacity in base power stations. If peak power had to be delivered, it was usually a competing situation to supply these needs at equal or cheaper prices compared to bulk electricity utilizing the existing over-capacity. Only specific demands for peak power have been sold at prices adequate to the actual peak power generating cost.

A new situation has developed over the past years due to the worldwide deregulation of the utilities. Accordingly, utilities are going to charge higher rates for periods of peak demand and, additionally, proportional to the load. As a consequence there will be by 2010 and later the situation, where PV systems will be more and more competitive with standard peak power utility supply (see Fig. 9). In Southern Europe PV generation starts to compete with utility peak power from 2007 on, whereas in Germany around 2020. The competition with bulk power occurs much later, projected to around 2030 for Southern Europe.

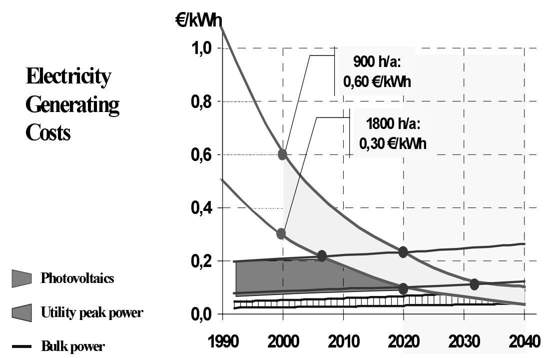


Fig. 9: Electricity Generating Costs for PV, as well as Peak and Bulk Utility Power

Considering facility management of buildings, particularly in southern regions in Europe, US and Asia, the peak demand for electricity occurs during midday as well as during the summer (Fig. 10). This coincides with the provision of peak utility power at corresponding prices. Hence there will be a substantial incentive to replace the needed high priced kW-hours from the grid by solar electricity, whose generation coincides with the peak load.

Accordingly, grid-connected PV installations will compete with new peak power stations required in the future. A recent study by Lahmeyer International [6] concluded that in addition to the existing 4000 GW power stations worldwide there will be an increasing power per year installed of about 100 GW in 2000 growing to 250 GW in 2030 (see Fig. 10).

Moreover, at a replacement period of 30 years about 130 GW per year need to be replaced. Part of these requirements will be satisfied by grid-connected cost competitive PV installations, starting around 2010 and reaching about 25 to 100 GW/year by 2030 (see Figs. 9 and 10), depending on the price development for peak and bulk utility power as well as the solar electricity generating cost as a function of time.

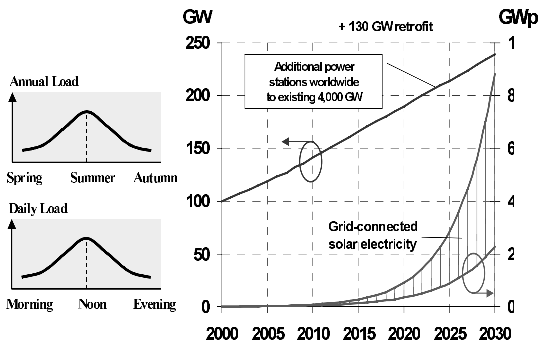


Fig. 10: Increasing Contribution of PV to Utility Power

2.2.5 Future Growth of the Four Market Segments

The future growth of the four market segments as function of time until 2010 is shown in Fig. 11, based on estimates by Maycock [7] and ourselves.

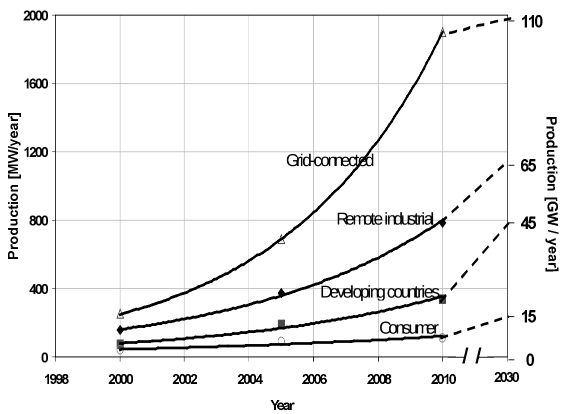
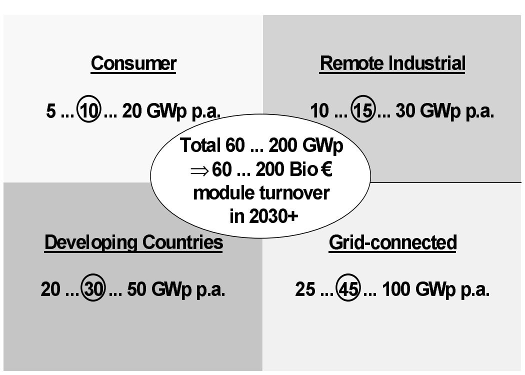


Fig. 11: Prediction of Development for the Four PV Market Segments

Using the 20 and 25 % annual growth rates from Fig. 4 a range of the respective market size for the four main market segments is shown in Fig. 12. The encircled intermediate values give in summary 110 GW which corresponds to the 22.5 % annual growth. The individual values for the four market segments are based on estimates



by Maycock [8] plausibility arguments and the wish that PV in developing countries in particular will grow with among the highest rates in the coming decades.

Fig.12: Market Size and Global Module Turnover in 2030 for the Four Market Segments for a 20 and 25 % Annual Growth Rate per Year

3. THE PV SOLAR ELECTRICITY INDUSTRY

3.1 Price Experience Curve

The projected growths of the market must be accompanied by production cost reductions. Production costs (and prices derived therefrom) are related to learning and experience in production, which is reflected in the level of production output. Following Boston Consult, the logarithms of the cost of a specific product and the corresponding accumulated number produced define cost learning curves. From the negative slope, typical for different technologies, the relative decrease of cost for doubling the cumulative number of produced products can be calculated. This relative cost reduction is called the learning factor. In the past years the approach of calculating learning factors has been transferred to a more complex methodology, yet easier to calculate for a whole industry. Using the same double logarithmic graph but typical market prices for the product, one again obtains a straight line, called a price experience curve.

In Fig. 13 (insert) the historic experience curve that traces world market module prices as a function of the accumulated module production is shown. This PV experience curve demonstrates a 20 % price decrease by doubling the cumulative volume; equivalent to that, half the production cost can be anticipated upon a tenfold increase of the accumulated output. It is noted that the experience curve does not directly contain a time scale. The learning and experience is affected by various influences that range from progress in research and development, to funding in the industrial and political environment, and on to interactions with the market.

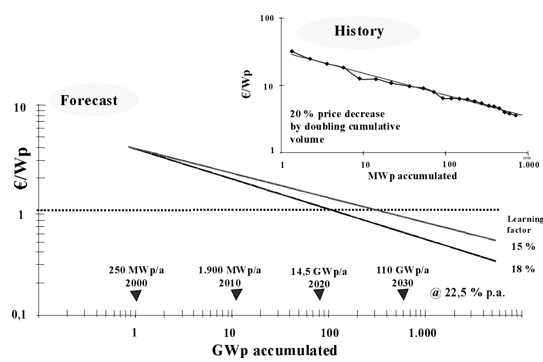


Fig. 13: Price Experience Curve for PV Modules

Since already industrialized PV technologies still promise potential for further development, and "next-generation" technologies are well underway, a strong confidence is justified to postulate that the experience curve will also extend into the future.

With increasing economy of scale material cost contributes relatively more and more to the total cost of a module. In order to account for that the anticipated learning factor is decreased from 20 % down to 18 % and even pessimistically to 15 %. The continued experience curve thus indicates, depending on the assumption of the learning factor between 15 and 18%, that the 1 €/W cost level will be reached at an accumulated production of 100 to 300 GW, which according to the projected growth of

22.5%/year will occur around 2021 and 2027, respectively.

3.2 Technology Road Map

The purpose of a road map is to draft approaches, by which the goals of a certain program can be reached. In this endeavor, the choice of PV technologies not only depends on the achievable efficiencies of production modules, but, even more important, also on the maturity of the technology in terms of its degree of industrialization, module manufacturing costs and the additional area-related balance-of-system costs, on the applicable energy pay-back times, and even raw materials reserves.

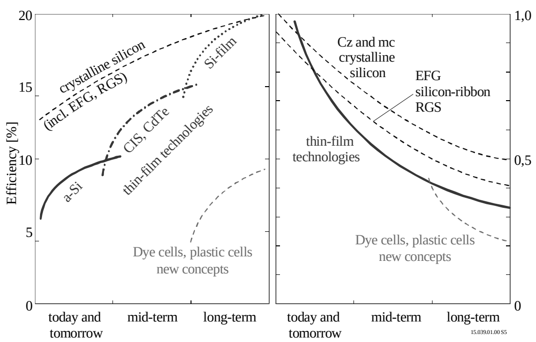


Fig. 14: Technology Road Map

Of all the modules globally sold in 2000, about 90% are made from crystalline silicon (c-Si). The silicon wafer material is monocrystalline, derived from Czochralski (Cz) processes, for about 40% of all c-Si modules, and multicrystalline (mc), derived from casting methods and ribbon technologies, like the edge defined film fed growth (EFG) [9], for about 60% of all c-Si modules. As pulled Cz and cast mc silicon derive already from well-known processes worldwide, an illustration of the EFG prepared wafers and subsequent automated inline cell production is shown in Fig. 15.

Fig. 15: RWE Solar Leadership in Si-Ribbon Technology

The dominance of silicon further extends into the thin-film technologies, particularly that based on hydrogenated amorphous silicon (short a-Si) [10].

Other thin-film technologies, based on copper-indium-gallium-diselenide (CIGS) and cadmium-telluride (CdTe), have reached sufficient maturity to be industrialized, and, in fact, have gone, or are about to go, into production. In 2000 their output still remained at the 1 MW/year level [1]. While their module efficiencies have exceeded, or have the potential to exceed, those of a-Si modules, it is not likely that these technologies may become the “work-horse” of PV solar electricity generation, since the materials availability, particularly indium and tellurium, will restrain the expansion of module production at about 20 GW/year for CdTe, and 70 GW/year for CIGS [11].

For many years to come, c-Si based technologies will play a dominant role (see Fig. 16). Although with increasing volume the supply of cost-effective “reject” silicon, a material not usable by the chip industry, but perfectly adequate for PV, will become scarce, the required silicon quantities will become sufficiently high to economically justify the production of a “solar-grade” silicon for the cell wafer production.

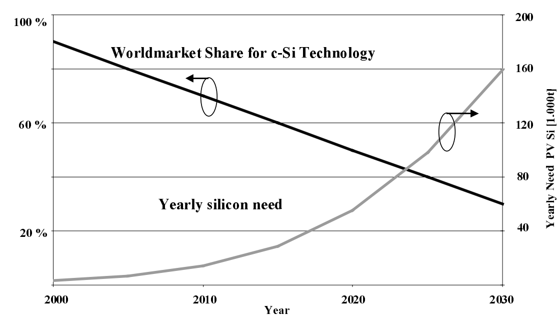


Fig. 16: .Market Share of c-Si Technology

Even at an aggressive growth of thin film technologies there are in 2030 at least 30 % of the global demand coming from crystalline silicon. This amounts to a solar-grade silicon consumption as high as 160,000 t in 2030 using Si feedstock consumption values from Schmidt et al [22].

Nevertheless, several advantages of thin-film technologies, such as

- large-area deposition,
- monolithic series connection of cells,
- shorter energy pay-back times,
- potential for lower module manufacturing costs,

will considerably stimulate a continued development of the thin-film technologies.

Thus both c-Si and thin-film technologies will play major roles in the future, but their shares are likely to shift towards thin-film technologies, mainly due to cost, and hence price considerations.

In the long term, the role of silicon may further extend into film-silicon technologies. The underlying process is a high-temperature CVD of silicon to thickness on the order of 10 µm on temperature-resistant substrates, like ceramic materials. Such an approach has already been transferred into a product (by Astropower), that in 2000 accounted for 2 MW/year (0,7% of the global market) [1]. Further developments in this area aim at combining the high efficiencies of c-Si with advantages of thin films, like lower materials consumption, larger deposition areas, and eventually monolithic series connection of cells [12].

New concepts for solar electricity are still in the research stages. Among those closest to a transfer into a piloting stage is the dye-sensitized nanocrystalline solar cell concept [13]. Further developments in this area are all-solid-state photoelectrochemical cells, where the liquid electrolyte of the former is replaced by a gel or solid ionic conductor. Finally, organic solar cells have been invented at efficiencies around 2% [14]. For all these concepts, it is too premature to make any prediction with regard to their role in any road map.

It must be emphasized that different technologies will coexist, even though their efficiencies may be quite different, but so may be their costs.

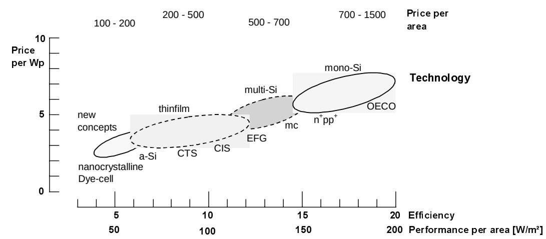


Fig.17: Area Related Price and Power Output for Various Technologies

This is even better recognized when plotting the various technologies in a graph like in Fig. 17. Starting from low 5 % efficiency and low price/W dye cells on the left side we go up to high 20 % efficiency and high price/W Cz-OECO (obliquely evaporated contact [23]) cells on the right. Other technologies (a-Si, II-VI, mc, Cz-std) are in between. Important is a look at the calculated values "price per area" across the top of the figure. If a customer needs high power output from a limited area (laptop, sun roof, etc.), he is prepared to pay a high price per W, and the high price per area is accepted. However, if PV modules are planned to be integrated into some 10,000 m² of a skyscraper facade, it becomes quite obvious that a low price per m² should be offered. This can be done most efficiently with a-Si today. As a result from the APAS study [15], all different thin-film technologies show about the same production cost per W_p (see Fig. 14). As the power outputs for CdTe and CIGS are higher compared to a-Si, there is a clear a-Si advantage for a lower price per module area. In addition, the thin layers of a-Si compared to II-VI compound semiconductors make it easier to manufacture semitransparent modules, which nicely fit into building integrated PV systems (see also Fig. 8).

3.3 Energy Pay Back Time

The energy pay-back time represents that time period over which a PV module generates the amount of energy that was required to produce it. It is thus a parameter that particularly in view of environmental considerations ought to be considered. While it is obvious that these time periods depend on the cumulated insolation and hence on the geographical location of the solar module installation (i.e. longer energy pay-back times at larger geographical latitudes), a comparison of the absolute values requires a clear definition of the energy consumptions that are to be taken into account for manufacturing the solar module. In Fig. 18 the energy requirements needed to produce a frameless solar module (based on own estimates and [16]) are compiled for two scenarios, that either take into account only the energies needed for the immediate steps to produce a silicon feedstock, wafers, cells and modules, or additionally include the energy requirements to produce all the raw materials needed (e.g. glass, plastics, etc.). In the latter case all electricity energy needs are changed to primary energy. The conversion factor electrical to primary energy typically is conservatively assumed to be 0.35. At an insolation of 1 kWh per W_p and year, that roughly applies to Central Europe, the energy need, expressed as kWh/W_p, equals the energy pay-backtime in years; for Southern Europe at about twice the insolation, the energy pay-back time corresponds to about one half the energy needs. While these data may vary significantly depending on the accuracy of data collection, it is safe to state that the energy pay-back times are far below the anticipated service life of modules, which today is 30 years and longer. Hence PV must be considered as an environmentally meaningful way of electricity generation.

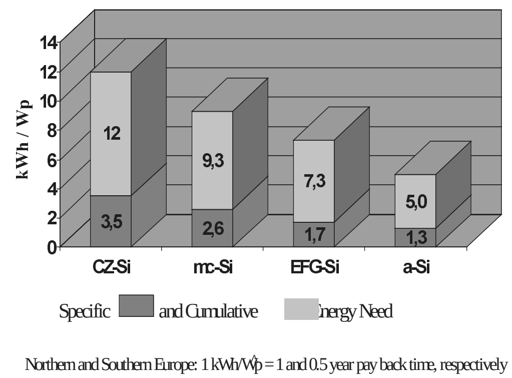


Fig. 18: Energy Need for Module Production

3.4 Cost Considerations

3.4.1 Dependence of c-Si module manufacturing cost on wafer cost

The price of the silicon wafer substantially affects the c-Si module manufacturing costs. Generally, the price of solar modules per W is governed by world market forces, and for the cell and module manufacturer it is imperative to hold his costs sufficiently below the market price. Different wafer types, most prominently monocrystalline or polycrystalline, fetch different prices, but also yield different efficiencies. Depending on the cell and module efficiency a manufacturer can achieve with a particular wafer type, his manufacturing cost varies (under the assumption of identical add-on costs per area for cell and module fabrication). The relative price and cost differences for various scenarios may be gleaned from Fig. 19. For example, using mc-wafers of unit cost that yield an efficiency of 15% will result in module costs of 100%. If the manufacturer succeeds in achieving higher efficiencies, say 16% due to a better cell architecture, his manufacturing costs decrease to 94%, i.e. his profit goes up by 6%. If he only achieves 13 %, his production cost increases to 115 %, i.e. his profit decreases by 15 %. Higher or lower wafer prices for different qualities require higher or lower efficiencies, respectively, to maintain the same module manufacturing costs. In particular, a 14 % efficiency with EFG-wafer, obtained on an average production value at RWE Solar, shows a clear competitive advantage.

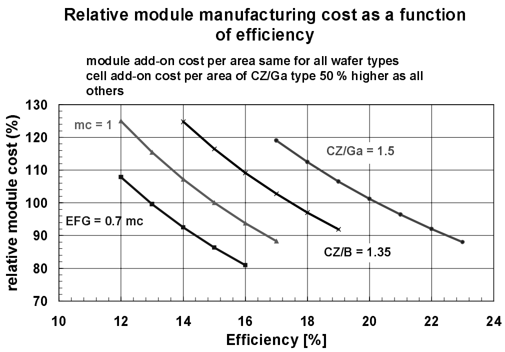


Fig. 19: Crystalline Silicon Module Cost as a Function of Efficiency for Different Wafer Technologies

3.4.2 Total PV System Cost

The total area required to install a certain power of solar electricity is inversely proportional to the module efficiency. Often it is argued that lower module efficiencies inevitably result in higher costs for a PV installation, due to the higher area-related balance-of-system costs. However, lower module manufacturer costs that are generally expected for the thin-film technologies, particularly for the a-Si technology (company private estimates and [15, 17]), may be sufficient to compensate for higher area-related costs, and actually lead to lower total system costs, compared to systems with higher module efficiencies.

Quantitatively, the following cost analysis will show the area-related system cost to mark a crossover in total system cost from being more favorable for a-Si to being more favorable for c-Si. The total cost C to the buyer of a PV system is composed of the module cost C_M [€/Wp], area-related system cost C_A [€/m²] or $C_A/10\ \eta$[€/Wp] (where η [%] is the total-area efficiency), and power-related system cost C_P [€/Wp], i.e.

$$C = C_M + C_P + C_A/10\ \eta \qquad (1)$$

This equation is evaluated under the following assumptions to yield Fig. 20.

- Module price of 4 €/Wp for c-Si modules (today's world market price); 3.20 €/Wp for a-Si modules (based on our estimates, and [15, 17]);
- Power-related system price of about 1 €/Wp;
- Total-area module efficiency of 14.0 % for c-Si, which is among the highest values presently commercially available [18]. In the context of area-related cost, the module efficiencies are to be referenced to the required area for module mounting, i.e. total module area defined by the overall dimensions. The corresponding more commonly stated cell efficiencies are higher.
  Stabilized total-area module efficiencies of 5.0 % to 9.0 % for a-Si; for frameless modules, the corresponding aperture efficiencies are typically 10 % higher.

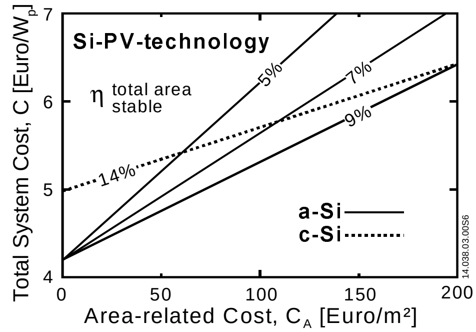


Fig. 20: Total System Cost as a Function of Area-related System Cost

Figure 20 shows the total system cost as a function of the area-related cost for both c-Si and a-Si under the above assumptions. As a result, a-Si installations have a cost advantage over c-Si, as soon as area-related costs fall below a certain limit of the area-related costs.

3.5 Structure of PV Solar Electricity Industry

Oriented at market growth the industry invested quite heavily in recent years as seen in the production capacity increase (Fig. 21).

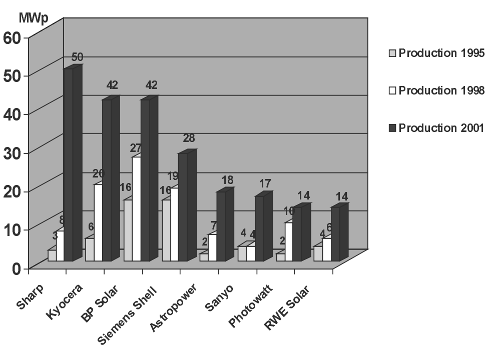


Fig. 21: Actual Production of Major Producers

In particular, the Japanese companies Sharp and Kyocera, due to the Japanese 70,000 roof program starting

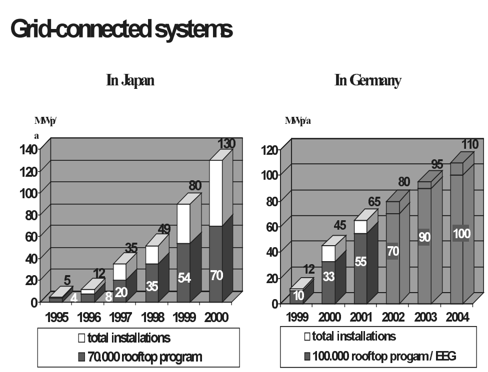


Fig: 22: Market Stimulation Programs

in 1996, recently passed the then two leading US companies Siemens and Solarex (the latter now integrated into BP Solar). This is a very good example for the fact that industry invests at their own risk quite intensively in a particular region, if a sustainable market in that region can be anticipated.

A similar situation is happening today in Germany, where the renewable feed-in tariff (EEG) of 99 Pfennig/kWh has created a big jump in the local market, and German companies invested in capacity increase, most pronounced at RWE Solar, who will add to the existing 20 MW cell line an additional 60 MW integrated EFG ribbon Si wafer-, cell- and module line, called SmartSolarFab®. It is interesting to note that each of the first five leading companies is soon approaching a 100 MW production capacity level. According to published data by MITI / NEDO (Japan), DOE (USA) and the Research and Development Ministry (Germany) as well as from company reports, it can be concluded that each of those five companies mentioned above (together with their integrated former companies) spent between 0.5 and 1.0 billion € up to now. This amount quite favorably reflects the respective company value, when comparing with the value of public traded companies (e.g. AstroPower, SolarWorld) and taking into account the net asset value as of today of each of those companies compared to the first five.

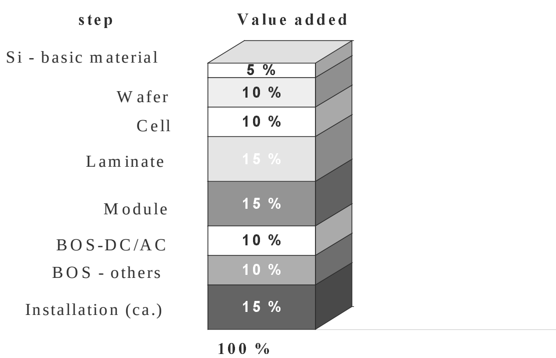


Fig. 23: Value Chain

The way the industry has organized itself within the value chain (see Fig. 23) is shown in Fig. 24.

Starting from the bottom there are only very few mainly chemical companies able to provide sufficient quantities of base materials at reasonable prices (e.g. feedstock Si, glass, metal pastes, gases). Subsequently there are two principally different routes prevalent – depending on company philosophy: If the focus is made to serve the end customer directly, we have a fully (wafer manufacturing included, like BP Solar) or partially vertically integrated system company (only solar cell and module production, like Shell Solar). On the other hand, if products are sold to distributors, Original Equipment Manufacturers (OEMs) and Module-producing Companies (ModCos), we call this an integrated component manufacturing company (like Kyocera in Japan, RWE Solar, Sharp and Siemens Solar). BOS (Balance of Systems) components are assumed to be delivered from individual companies (like DC-AC inverter companies).

The substantial investment today for a fully integrated 100 MWp production facility is in the range of 200 million €. This holds both for crystalline (wafer-, cell- and module fabrication) as well as for high-quality thin-film (amorphous Si, II-VI compound semi-conductors) productions plants. Specific investments in the future may decrease similarly to price reduction scenarios by 5% per year due to higher productivity of future manufacturing equipment.

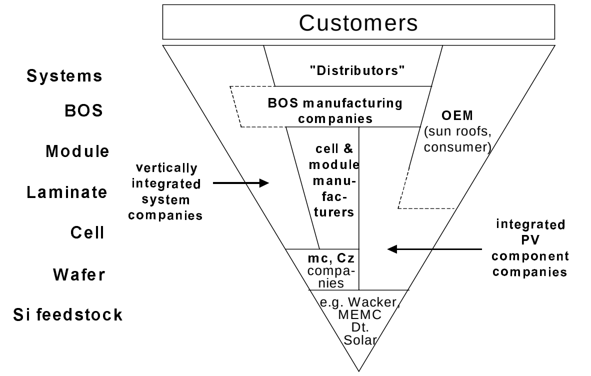


Fig. 24: Various Company Approaches within the PV Value Chain

4. PV SOLAR ELECTRICITY IN THE CONTEXT OF A FUTURE GLOBAL ENERGY SUPPLY CHAIN

One important aspect of this paper is the demonstration of an important new industry to grow within the next two to three decades. The anticipated turnover of global module sales on the order of 100 billion € annually by 2030 underlines a significant new business carried by new employment in the order of several million jobs, if BOS component manufacturing as well as installation, trading, marketing and sales for complete PV solar electricity systems are included.

As the now completed Solar Electricity Jigsaw Puzzle demonstrated, PV Solar electricity indeed combines the following prime features to become a new-millennium industry, namely:

- **Fast growing market**
  Over the last 5 years, an average global market growth of 27% per year has occurred. As the main market segments being served today show widespread acceptance and imply a sound demand, a market pull for many years to come, with a continued annual growth between 20 and 25 % may be anticipated for the future.
- **Substantial business in coming decades**
  The anticipated module turnover around 2030 will be in the range of 100 billion € per year – a market that will support employment on the order of several million people worldwide.
- **Global energy justice**
  Providing affordable power to the billions of people in developing countries.
- **Shift to service society**
  The PV industry enables the industrial countries to shift from an industrially oriented employment society to a service society by mass-producing with highest productivity high-tech PV solar electricity products. To maintain or even to increase the gross national products, the service-oriented society is bound to create the corresponding employment. Such shifts in the employment society have occurred before (see Fig. 25).

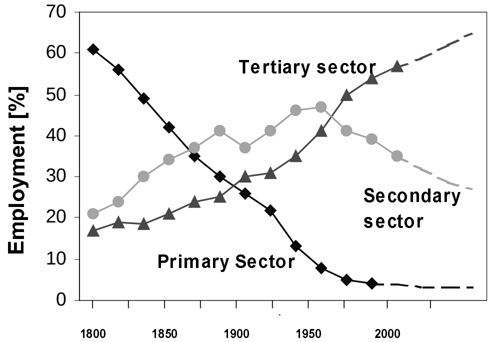


Fig. 25: Employment in Germany according to Production Sectors [19]

As a crude analogy one might consider the agricultural employment, respresented by the primary sector, that steadily has declined substantially, yet the volume of agricultural products has increased to this date. (The secondary and tertiary sectors represent the industrially-oriented and the service-oriented societies, respectively.)

- **Environmentally sound**
  Almost needless to say, but worth emphasizing, solar electricity products generate electricity with the least impact on, and perturbation of the environment.

So far, in terms of global electricity contribution this new business does not yet play an important contribution, as seen in Fig. 26, where at the 22.5 % annual growth level a worldwide contribution of 1% is reached around 2030 and a 10% level may be reached around 2040. These numbers are based on the already mentioned 4,000 GW worldwide electricity power generating capacity [6], the global electricity energy production in 1998 of about 14,000 TWh [20] and assuming 1.5 kWh per year generated by 1 W_p of solar modules (for comparison reasons: the worldwide primary energy consumption in 1990 was about 100,000 TWh [20]).

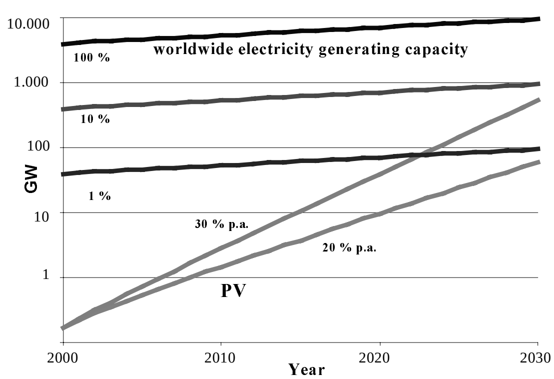


Fig. 26: Development Prediction of Worldwide Electricity Capacity in Relation to PV Solar Electricity Contribution

A future projection for primary energy consumption was recently published by Shell [21] as seen in Fig. 27.

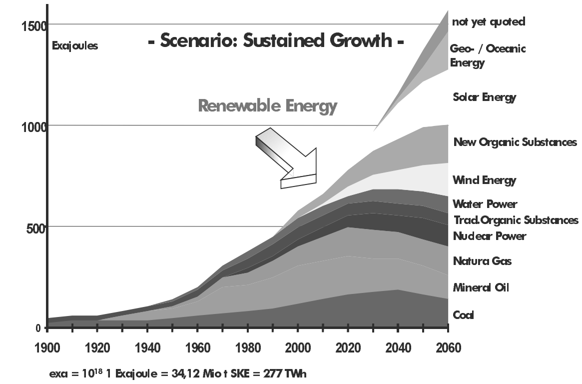


Fig. 27: Global Energy Consumption (sustained growth) Source: Shell [21]

In the global primary energy picture PV solar electricity shows visibility in 2040 and later very much in line with our projection. At the very end the question remains as to how fluctuating renewable energy sources – like wind and solar electricity – may serve continuously the energy needs of mankind, assuming that electricity storage of huge GWh amounts daily, and even more seasonally, is economically prohibitive. In order to solve that problem two solutions exist: firstly a global hydrogen society, and secondly a worldwide high tension DC grid. Whereas hydrogen will undoubtedly play an increasing and later dominating role in fuel cells and turbines for global mobility purposes, it remains to be seen, where the stationary energy suppliers will take their energy from. If a worldwide high tension DC grid is able to transport GWh of electricity half around the globe at similar – even slightly higher – losses compared to a hydrogen pipeline and storage, there would be a big advantage for the world electricity grid, as there are not the twofold losses first by electrolysis of water to hydrogen and second by fuel cells converting hydrogen back to electricity again.

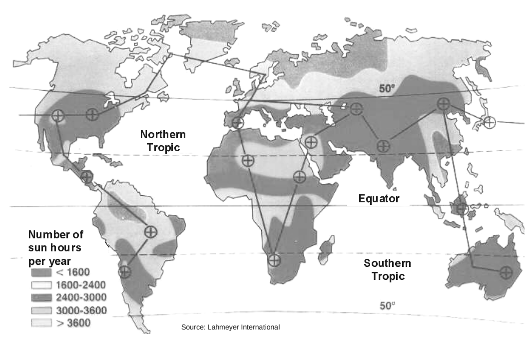


Fig. 28: Vision for a Global and Sustainable Energy Supply

Looking at Fig. 28 and remembering that the size of one dot like the one in the Sahara dessert would be sufficient to supply the world's annual primary energy needs, it can be concluded that by combining all renewable energy sources, there is a good solution available for future generations of mankind, namely to utilize the very best fusion reactor – the sun.

\

ACKNOWLEDGMENT

I would like to thank the entire RWE Solar Team in Alzenau, Heilbronn, Munich and Billerica/Boston for their enthusiastic contributions over many years, which took RWE Solar to the place internationally where we are today. The outstanding support from our mother company RWE Solutions AG is greatly appreciated, as well as the financial support for R & D projects by the German Federal Ministry for Economy and Technology (BMWi), the Bavarian State Ministry for Economy as well as the European Commission in Brussels and the Department of Energy of the US. In particular the excellent help from Horst Schade is greatly honored, who added a lot of valuable thoughts and well formulated text contributions to this publication.

REFERENCES

1. PV News (P. D. Maycock, Ed.), vols. 10 (1991), 16 (1997), 20 (2001)
2. P. D. Maycock, E. N. Stirewalt, Proc. IEEE Specialists Conference (1982), p. 1215
3. Universität Gesamthochschule Kassel
4. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ)
5. RWE Calculation Standards for North-Rhine Westphalia
6. Lahmeyer International, private communication (1998)
7. P. D. Maycock, Renewable Energy World 2 (July 1999), p. 62
8. P. D. Maycock, Renewable Energy World 4 (July/August 2001), p. 144
9. W. Schmidt, B. Woesten, J. P. Kalejs, Progr. in Photovoltaics, to be published
10. P. Lechner, H. Schade, Progr. in Photovoltaics, to be published
11. B. A. Andersson, Progr. Photovolt. Res. Appl. 8, 61 (2000)
12. T. Buschbaum, S. Will, H. v. Campe, D. Nikl, Abschlussbericht Bayrischer Forschungsverbund Solarenergie (1998)
13. M. Grätzel, Progr. Photovolt. Res. Appl. 8, 171 (2000)
14. L. Schmidt-Mende et al., Science 293, 1119 (2001)
15. U. Ugalde, J. Alonsdo, T. Bruton, J. M. Woodcock, K. Roy, K. De Clerq, Proc. 14th European PVSEC (Barcelona 1997), p. 897
16. E. A. Alsema, P. Frankl, K. Kato, Proc. 2nd World Conference on PVSEC (Vienna 1998), p. 2125
17. J. M. Woodcock, H. Schade, H. Maurus, B. Dimmler, J. Springer, A. Ricaud, Proc. 14th European PVSEC (Barcelona 1997), p. 857
18. Photon International (April 2001), p.29
19. Yearly statistical books for the Federal Republic of Germany (1960, 1994)
20. RWE, Chancen und Risiken der zukünftigen Weltenergieversorgung 2000 (2000)
21. Deutsche Shell AG (1999)
22. W. Schmidt, B. Woesten, J. P. Kalejs, 16th European PVSEC (Glasgow 2000), p.1082
23. R. Hezel, A. Metz, 16th European PVSEC (Glasgow 2000), p.1091